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Ecological Footprint assessment for targeting climate change mitigation in cities: A case study of 15 Canadian cities according to census metropolitan areas

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ABSTRACT

As the world moves towards a carbon-free future, cities have been identified as key hubs for change. They have the greatest ability to quickly develop more efficient systems and implement climate change mitigation policies. Moreover, cities will become the destination of a population migration as humanity grows globally to a population of 11 billion. In this case study, we show that the applicability of the Ecological Footprint, an overarching outcome measure of resource consumption, for targeting climate change mitigation in cities. We focus on the carbon Footprint subcomponent of the Ecological Footprint, and further translate and disaggregate the carbon Footprint into detailed classification of individual consumption according to purpose (COICOP) and analyze the Footprint of consumption associated with each of these categories for 15 Canadian cities according to census metropolitan area (CMA), from each province. The Ecological Footprint of CMAs was calculated from the consumption land use matrix (CLUM) of Canada, by scaling results according to the annual national survey of household spending from 2010 to 2015. The expenditure in electricity was also scaled with the carbon intensity factor. Our findings indicate that the carbon Footprint remains the largest contributor of the Ecological Footprint of CMAs. The carbon Footprint associated with housing varied significantly with the source of electricity production. CMAs relying on renewable energy sources have a substantially lower carbon Footprint than those relying on fossil fuel energy. The carbon Footprint associated with the operation of personal transportation was the second largest among all consumption categories. Financial services is the largest share of the carbon Footprint from service consumption. Clothing consumption caused most of the goods' carbon Footprint. A better understanding of urban planning of Canadian CMAs and promoting local consumption will improve carbon mitigation and long-term sustainability.

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1. Introduction

With the growing rate of urbanization, climate change mitigation must be addressed at the city scale. As a result of recent population migration and concentration in cities, greenhouse gas (GHG) emissions have also increased. (Glaeser and Kahn, 2010; Jones and Kammen, 2011; Weber and Matthews, 2008). Household consumption represents a large share of North American GHG emissions and households have been estimated to generate 80% of total American GHG emissions (Jones and Kammen, 2011). Housing and transportation are the two most carbon-intensive consumption categories, because of direct fossil fuel combustion, fossil fuel used in electricity generation, and indirect supply-chain emissions. Scientific literature contains many studies that define actions to decrease carbon Footprint (CF) (Gill et al., 2007; Nowak et al., 2006; Sarralde et al., 2015; Ottelin et al., 2017; Treu et al., 2017; Veeramani et al., 2017). Long-term planning has the potential to significantly reduce GHG emissions through the transition to more efficient urban forms. Urban

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List of abbreviations

CF	Carbon Footprint
CLUM	Consumption land-use matrix
COICOP	Classification of individual consumption according to purpose
COP 21	21st yearly session of the Conference of the Parties to the 1992 United Nations Framework Convention on Climate Change
CPI	Consumer price index
CPIC	Comparative CPI
CPIR	Relative CPI
EE-MRIO	Environmentally-extended multi-regional input −output
EF	Ecological Footprint
GFN	Global Footprint Network
GHG	Greenhouse gas
GFCF	Gross fixed capital formation
Gha	Global hectares
GTAP	Global Trade Analysis Project
kg CO_2 eq	Kilogram carbon dioxide equivalent
MRIO	Multi-regional input-output
$MtCO_2$ eq	Mega tonne carbon dioxide equivalent
NFA	National Footprint Accounts
SF	Scaling factor
SHS	Survey of household spending

planning affects housing types, commuting distances, availability of different goods and services, social contacts and emulation (Heinonen and Junnila, 2014). Cities represent the nerve centre for research on low-carbon indicators in order to find measures necessary reduce human impacts on his global ecosystem. While many indicators and methodologies are available, this case study shows how the Ecological Footprint (EF) can be used to support climate change mitigation at the city level by focusing on the CF subcomponent and targeting influential consumption sectors for mitigation measures.

1.1. The Ecological Footprint and its components: carbon footprint

The Ecological Footprint is a measure of human demand on natural resources and services. Based on the ecological concept of carrying capacity, EF was introduced and developed as a practical measure of the bioproductive area required to support societal metabolism for a given set of human consumption activities (Rees, 1992; Rees and Wackernagel, 1992; Čuček et al., 2012). The EF metric, which sums up the amount of biologically productive land and sea required for a given population or activity (Kitzes and Wackernagel, 2009), is one of two metrics used in the Ecological Footprint accounting framework in order to inform on the conditions of sustainability. Where EF represents the consumption side of the accounts, biocapacity represents the biosphere's regenerative ability to meet these consumption demands. By comparing these metrics, we can evaluate whether demands of a given population or activity towards the limited capacity of the biosphere to offer its goods and services based on fundamental sustainability principles (Daly, 1990). In the context of sustainable development, these principles assert that renewable resources may not be used faster than they are regenerated and pollution should not be emitted faster than it can be assimilated. The EF is a composite indicator of sustainability (Čuček et al., 2012).

The Ecological Footprint is made up of six Footprint sub-components: cropland, grazing land, forest products, fishing grounds, built-up land, and carbon Footprint; which are provided for by 5 biocapacity sub-components. Here, forest land provides biocapacity for both the consumption of forest products such as wood and fibre products, as measured by the forest product Footprint, and assimilation of anthropogenic CO_2 waste, as measured by the carbon Footprint (Borucke et al., 2013). Ecological Footprint and biocapacity are measures of flows and expressed in global hectares (gha). A global hectare is a flow of resources generated by a hectare of world-average bioproductive land area. As a metric that informs on these overarching principles of sustainability, Ecological Footprint accounting has been widely used by the scientific community, intergovernmental organizations, national and sub-national governments and Non-Governmental organization bodies as an overarching measure to inform sustainability.

The National Footprint Accounts (NFA; Global Footprint Network 2017) are the main country-level application of Ecological Footprint Accounting (Lin et al., 2015). The NFAs follow a bottom-up consumption based approach by accounting for the production (or harvest) of primary goods and adjusting for the trade of embodied biocapacity. Results are usually categorized by land use demand as the six Footprint sub-components above, however, they can also be re-categorized by the final consumption category, which provides increased resolution by the type of final consumer (government, gross fixed capital formation, and households) and the type of final consumption (food, housing, transportation, goods, and services). A commonly applied method to obtain results by the final consumption category is the application of environmentally extended multi-regional input-output (EE-MRIO) approach (Ewing et al., 2012). This approach provides country-level resolution by consumer types and further by the economic sector and can be further translated into detailed consumption categories according to the United Nations Classification of Individual Consumption according to Purpose (COICOP) categories (Wiedmann et al., 2006). This method is consistent with recent top-down city assessments (Baabou et al., 2017).

Globally, the carbon Footprint (CF) is the largest component of the Ecological Footprint, making up 65% of the total Ecological Footprint (Global Footprint Network, 2016a) in 2011. Canada had the sixth-largest per capita EF globally, at 8.19 gha per capita in 2011. Similar to most high-income countries, the CF of Canada represents a large percentage of Canada's total EF (65%, Fig. 1). Here we present data using the year 2011 as the reference year to be consistent with the methodology to derive the National consumption land use matrix (CLUM).

The carbon Footprint component of the Ecological Footprint has two attributes that differ from the common interpretation of a carbon footprint, which pertains strictly to the emission of CO_2 in units of mass. First, the carbon Footprint component of the Ecological Footprint as used in this study, represents the consumption CO_2 emissions, transformed and expressed as the area of world average bioproductive forest land needed to sequester these emissions, or global hectares. As described by Mancini et al. (2016) this conversion makes anthropogenic CO_2 emission comparable to other demands on biocapacity. Second, this study applies the carbon Footprint of consumption rather than the Footprint of production.

1.2. Review of existing city's level Ecological Footprint assessments

Since the first city EF assessment of Santiago de Chile by Wackernagel (1998), 63 city EF assessments have been documented in the literature across 20 countries (Baabou et al., 2017). Most recently, Baabou et al. (2017) calculated the EF of 19 Mediterranean cities with a top-down approach based on a multi-regional input-output analysis using data on average household expenditures and

national CLUM. While EF was found to be variable even within the same geographic area and within countries, the CF remains the largest of the Footprint subcomponents. This study on Mediterranean cities provides many insights and relies on economic data on household consumption based on time series analysis, which could be further verified. Other cities assessment compared only a small number of cities in the same study.

To calculate the city's EF, one of two approaches is generally followed. The bottom up methodology follows the same approach as the NFA (Borucke et al., 2013), using production, import, and export data specific to the local population and boundary such as city or region border (Moore et al., 2013). Using this bottom up data, the consumption Footprint is calculated as the sum of production and imported Footprints, after deducting exported Footprints. The limitation of this method is data availability and selection, which can prevent a consistent and comparable approach among many cities. The top down methodology is based on a scaling of national EF results. In the top down approach paired data is collected on the consumption patterns of the specific local population, this data is then used to scale the EF in specific consumption categories based on the ratio of local to national average data. The challenge of this approach is to access datasets that are consistent across many cities over the same time periods. As more paired datasets are collected, the accuracy of measurements is refined. These calculations can be further refined using complementary datasets such as local energy intensity (see Section 2.2).

A early study on the EF of Canadian cities was reported by Wilson and Anielski (2005), who first estimated EF for 20 Canadians' cities based on average household expenditures data and the matrix of EF components of Canada. These authors found that Canadians' cities have variable EF per capita, from 6.87 gha per capita for Great Sudbury (Ontario) to 9.86 gha per capita for Calgary (Alberta) in 2005. In addition, only five cities were under the national average Footprint. Higher EFs are associated with more carbon-intense energy consumption, whether electricity, heating or transportation. The absolute results from Wilson and Anielski (2005) cannot be directly compared to results found here because of differences in methodology. The top down assessment was based on a national footprint results prior to the development of the NFA, and directly applied expenditure data to scale EF components, compared to more recent studies, which first apply an environmentally extended multi-regional input–output (EE-MRIO) model to derive a matrix of consumption category Footprints and their respective land use footprints (CLUM), to which expenditure data can be more accurately and consistently applied. Since this study, both national (Lin et al., 2016) and sub-national methodologies have been updated and follow a set of proposed common standards (Global Footprint Network, 2009) to achieve consistent results.

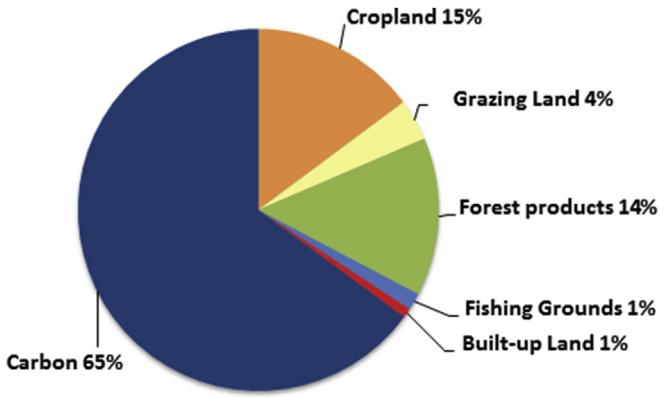

Fig. 1. Canadian Ecological Footprint by land use type (Global Footprint Network, 2016b).

1.3. Objective of this paper

This paper describes a quantitative framework to identify and compare solutions to reduce the carbon Footprint and a case application to 15 Canadian cities according to census metropolitan areas. Here we focus on the carbon Footprint subcomponent and further analyze disaggregated components of CF by consumption category in order to identify target areas for climate change mitigation. The originality of this study is the application and framing of urban sustainability solutions using an aggregate metric to monitor high-level outcomes on the carbon Footprint. The economic data is from the national Survey on Household Spending for six years.

2. Data and method

The data analysis followed a three-step process: National Footprint Accounts, environmentally extended MRIO analysis and scaling procedures at the city level (Fig. 2). Ecological Footprint data on production from the National Footprint Accounts (2016 Edition) were used to as input to a Footprint extended MRIO model based on the Global Trade Analysis Project (GTAP) 9 database (Aguiar et al., 2016). The resulting Ecological Footprint categorized into final demand in 57 economic sectors and across from GTAP 9 are then translated into COICOP consumption categories from which the national CLUM of Canada is derived. To maintain consistency, 2011 data were used as input data from the NFA in conjunction with 2011 economic data from GTAP 9. Here we follow a top-down approach to estimate cities' EF starting with the national CLUM of Canada, as used by a 2011 study on Calgary (Kuzyk, 2011). We then scale the national data to each city using average household expenditures, similar to Wilson and Anielski (2005) and CO_2 intensity through energy factor. Using the base year of 2011, we calculated the EF of cities using supplemental scaling data from 2010 to 2015. The NFA has data up to 2013, while the EE-MRIO model (global economic model to translate land use to economic sectors to final-consumption type) was a 2011 model, so we present all data in 2011, then used CMA data to scale 2011 to different years, and Canada was not scaled again.

2.1. Cities as census metropolitan area

The 15 city boundaries are defined according to their census metropolitan area (CMA). They are located in the 10 provinces (ordered from east to west): St John's, Halifax, Charlottetown, Saint John, Quebec City, Montreal, Ottawa-Gatineau, Toronto, Winnipeg, Regina, Saskatoon, Edmonton, Calgary, Vancouver, and Victoria. Hereafter, Ottawa-Gatineau is referred to as Ottawa and Quebec City to Quebec. The number and size of CMAs available in the national survey of household spending (SHS) is limited by the sample design from Statistics Canada. Their goal is to obtain estimates of similar quality across all provinces, but not for all CMAs in Canada. Because of this technical limitation, the CMAs in this study do not represent the largest cities in Canada. The 15 CMAs represent the capital of the provinces and of Canada to have a provincial outlook, then the cities in economic importance. Fig. 3 shows the geographic location of the cities, along with their Ecological and carbon Footprint.

The method estimates EF and by extension CF of these metropolitan regions based on to two types of data:

- detailed average household expenditures provided by Statistics Canada, from a personalised database from the annual SHS between 2010 and 2015;

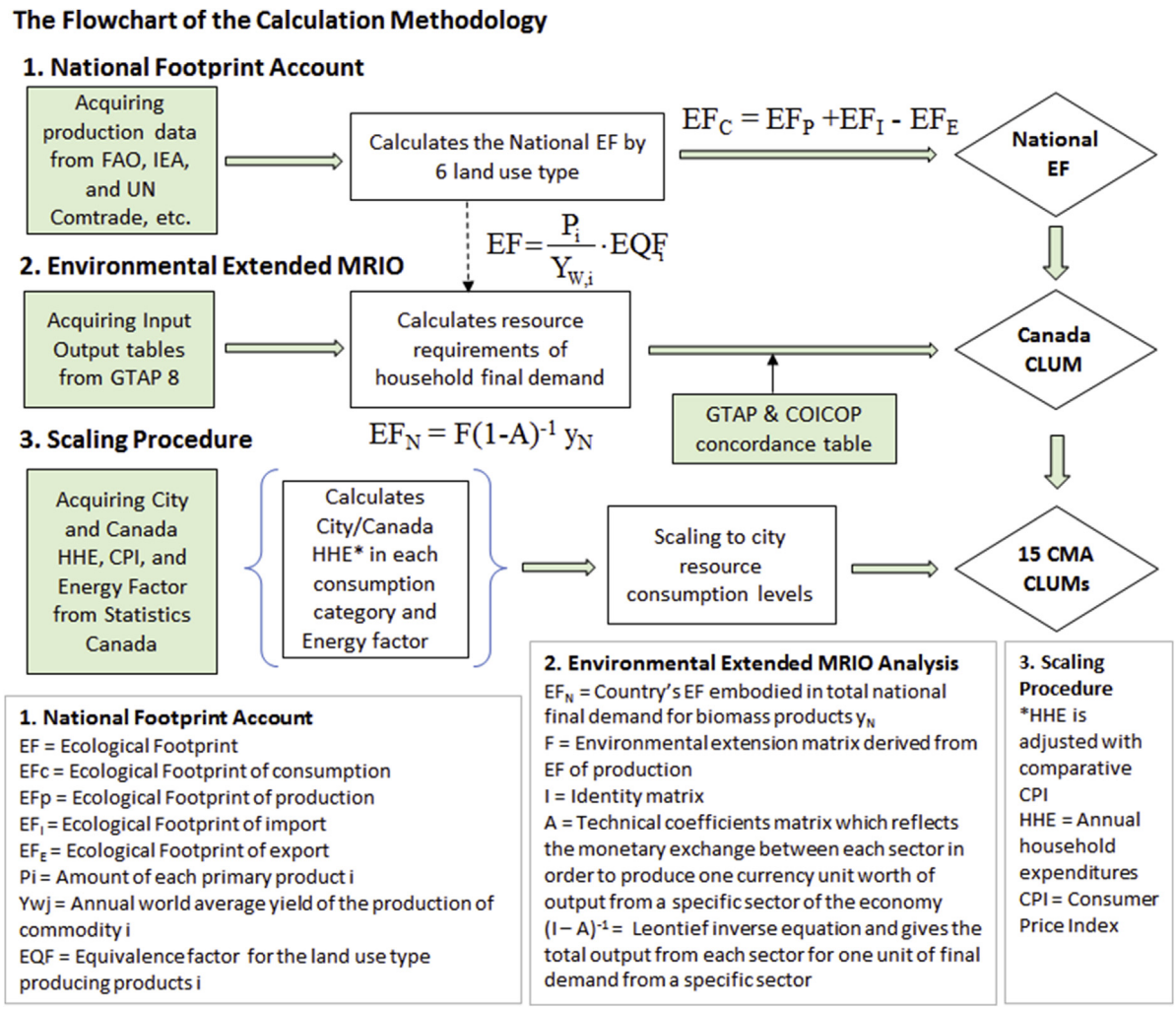
The Flowchart of the Calculation Methodology
1. National Footprint Account
Acquiring production data from FAO, IEA, and UN Comtrade, etc.
Calculates the National EF by 6 land use type
$EF_C = EF_P + EF_I - EF_E$
National EF
$EF = \frac{P_i}{Y_{W,i}} \cdot EQF_i$
2. Environmental Extended MRIO
Acquiring Input Output tables from GTAP 8
Calculates resource requirements of household final demand
Canada CLUM
GTAP & COICOP concordance table
$EF_N = F(1-A)^{-1} y_N$
3. Scaling Procedure
Acquiring City and Canada HHE, CPI, and Energy Factor from Statistics Canada
Calculates City/Canada HHE* in each consumption category and Energy factor
Scaling to city resource consumption levels
15 CMA CLUMs
1. National Footprint Account
EF = Ecological Footprint
EFc = Ecological Footprint of consumption
EFp = Ecological Footprint of production
EF_I = Ecological Footprint of import
EF_E = Ecological Footprint of export
Pi = Amount of each primary product i
Ywj = Annual world average yield of the production of commodity i
EQF = Equivalence factor for the land use type producing products i
2. Environmental Extended MRIO Analysis
EF_N = Country's EF embodied in total national final demand for biomass products y_N
F = Environmental extension matrix derived from EF of production
I = Identity matrix
A = Technical coefficients matrix which reflects the monetary exchange between each sector in order to produce one currency unit worth of output from a specific sector of the economy
$(I-A)^{-1}$ = Leontief inverse equation and gives the total output from each sector for one unit of final demand from a specific sector
3. Scaling Procedure
*HHE is adjusted with comparative CPI
HHE = Annual household expenditures
CPI = Consumer Price Index

Fig. 2. Adjusting CLUM to municipal scale methodology.

- Canada's CLUM (2011) provided by Global Footprint Network (GFN).

In this study, data are classified according two sources: Global Footprint Network which uses a classification for the CLUM categories and Statistics Canada with the expenditures categories (over 300 subcategories). A concordance table was made to compare each category from a classification to another. Energy factor is also used to estimate CF associated to electricity, gas and other fuels only. Its calculation is based on CO_2 intensity, which represents the amount of GHGs per unit of gross domestic product (Environment and Climate Change Canada, 2016a). Its units are mega tonne CO_2 equivalent (Mt CO_2 eq).

In the Surveys of Household Spending, the average age of the reference person answering the survey on the behalf of the household in the CMAs is 49.7 ± 2.0 years. The SHS was personalized to provide information according to building types (All dwellings, single detached, single attached, apartments and other) and modes of occupation (all, owners with or without a mortgage and renters). The study of the EF of Canada according to building type is found in Jouaneau et al. (2016). This case study considers all dwellings to have an overview of the situation and due to data availability in the 15 CMAs. Only expenses for the principal accommodation were considered; expenses for other accommodation (owned vacation home and other secondary residences, other owned properties, accommodation away from home) were not considered, while they can be relevant to study parallel consumption. The SHS data quality check was performed by comparing the total expenses reported and the total calculated with the detailed categories, including income taxes and charitable contributions (although not considered in the CF and EF calculations). Both totals were usually comparable with a difference of up to 10% difference, except in Ottawa, Vancouver and Victoria which have more years with lower matching total (Supplementary Spreadsheet 1). One reason could be that the consumption of these citizens happens outside the categories provided by the SHS. Their EF and EC can appear lower and more variable due to data quality. In Ottawa and Victoria, the food data was missing for two and one year and the average was calculated based on years available, as mentioned in 3.6. The difference between both total is due to the fact that Statistics Canada does not report the detailed data when a minimum number of reply is not reached, thus the sum of detailed categories was always lower than the total expenses reported per CMA.

CLUM is composed by 3 major categories: household consumption, which represents a direct consumption expenditure in the categories of food, housing, transportation, goods and services; government consumption, which represents direct government expenditures associated with ongoing government functions; and gross fixed capital formation (GFCF), which represents the expenditure on long-term, durable or "fixed" physical assets such as

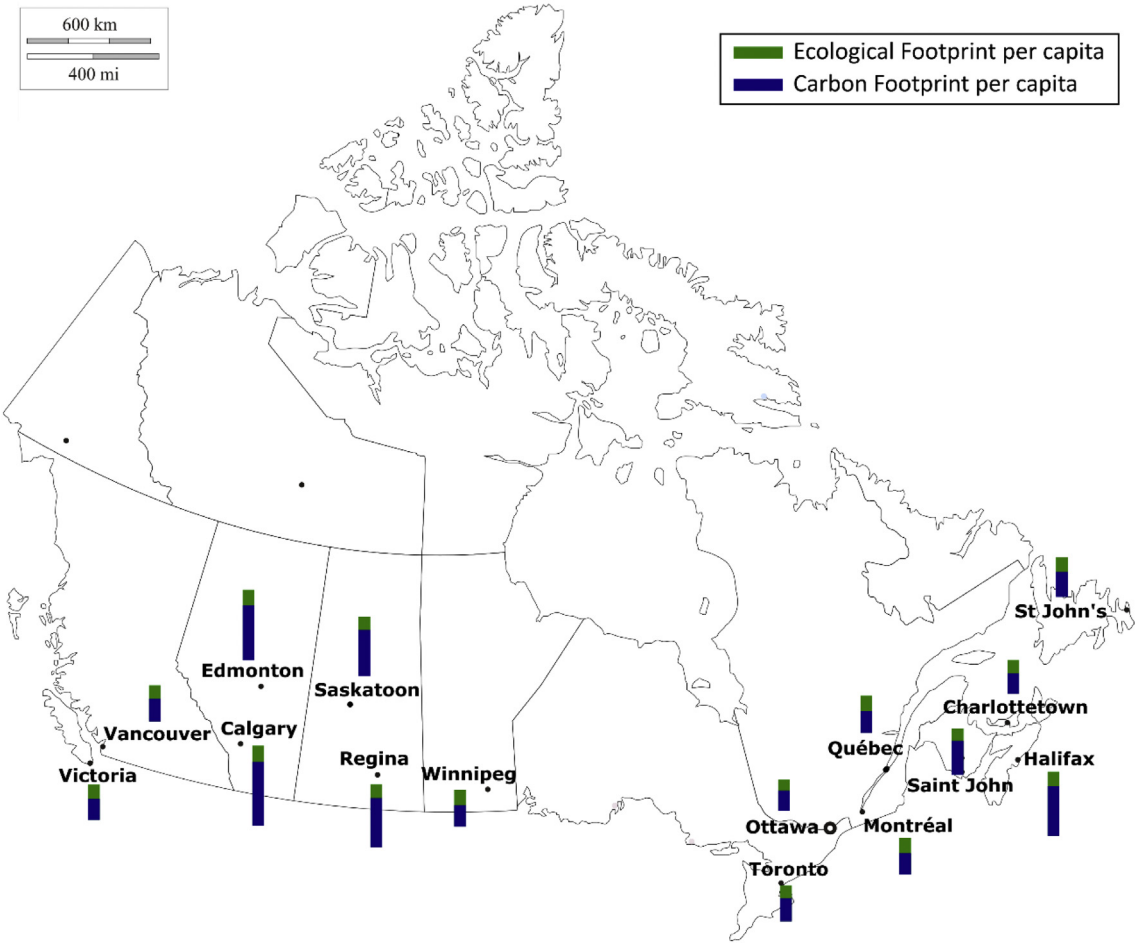

Fig. 3. Location of 15 census metropolitan areas (CMAs) in Canada and overview of Ecological Footprint and carbon Footprint per capita.

buildings, infrastructure, or other land improvements by households, firms and governments. The EF associated to the household consumption, 5.29 gha per capita, represents 65% of total Canadian EF in 2011. Government and GFCF represent respectively 0.86 (13%) and 2.04 (31%) gha per capita (Fig. 4). The following study focuses on household Ecological Footprints, consequently, government and GFCF inputs are not considered.

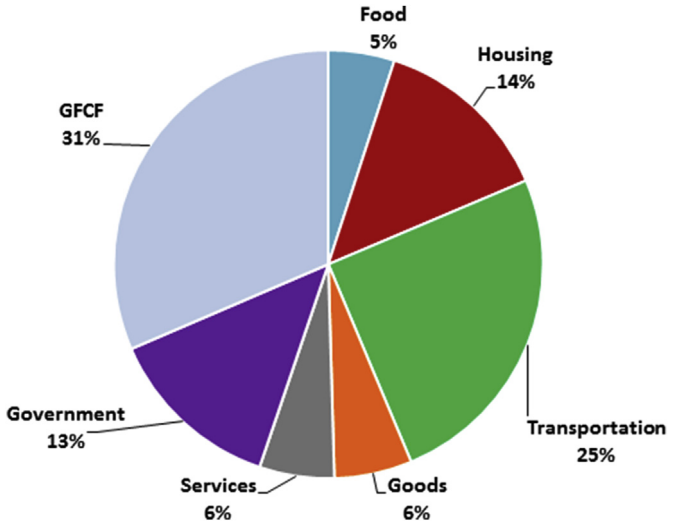

Fig. 4. Canadian Ecological Footprint by consumption categories (Global Footprint Network, 2016b).

2.2. Data analysis

For the analysis of 15 Canadian cities, the CLUMs are scaled with the detailed personalized CMA's household consumption statistics collected at the annual national SHS from 2010 to 2015, reclassified accordingly to the COICOP categories. The scaling procedure includes adjusting the households' expenditure with the consumer price index (CPI) available for each city (Gouvernment of Canada, 2017). The heating consumption of a province is scaled in terms of its CO_2 intensity (Environment and Climate Change Canada, 2016a). The variability in the figures indicate the standard deviation of the data on the y axis for 2010–2015, unless indicated differently in the text. While the subcategories are presented, the standard deviation is reported on the total. The CMAs with less variation means that the population surveyed was more homogeneous, while more variation suggests more heterogeneous consumption habits over the years. The boundaries of the CMAs can also slightly change over the years. The data was not further adjusted for taxes on specific product or subsidies on services, which could be relevant in another study. The results from the SHS are average data and are not representative of every Canadian.

To begin, household expenditures from the annual national survey must be expressed per capita to be comparable to Canadian EF data given in gha per capita.

$$Expenditures\ per\ capita = \frac{Expenditures\ per\ household}{Average\ household\ size} \quad (1)$$

Scaling factors (SF) are computed according to Equations 2 and 3. CPI is unique for each city *i* and depending on consumption category *j*. Statistics Canada gives us two kinds of CPI: relative and comparative. To compare cities at the national scale, it is necessary to use comparative CPI (CPIC) because relative CPI (CPIR) give us information only at the provincial scale. Nevertheless, Statistics Canada does not a CPIC for 3 CMAs: Quebec, Saskatoon and Calgary. Then, for these cities, CPI has been adjusted than to comparative CPI of Montreal, Regina and Edmonton respectively according to Equation (2).1 where the city i and j are in the same province. The data on expenditure per category is presented in Supplementary Electronic Spreadsheet 2.

$$CPI_{Comparative_i} = \frac{\left(CPI_{Comparative_j} \cdot CPI_{Relative_i}\right)}{CPI_{Relative_j}} \quad (2)$$

$$SF_{i,j} = \frac{\frac{Expenditures\ households_{i,j}}{Expenditures\ households_{CA,\ j}}}{\frac{CPI_{i,j}}{100}} \quad (3)$$

Energy factors are computed according to Equation (4) based on CO_2 intensity for each city *i* provided by Environment and Climate Change Canada (2016a,b) in *National Inventory Report 1990–2015: Greenhouse Gas Sources and Sinks in Canada.*

$$Energy\ factor_i = Energy_i = \frac{CO_2\ intensity_i}{CO_2\ intensity_{Canada}} \quad (4)$$

Finally, CF associated with each city *i* is computed according to Equation (5). The energy factor is used only for the component "Electricity gas and other fuels" according to Equation (6).

$$CF_i = CF_{CA} \cdot SF_{ij} \quad (5)$$

$$CF_{i_{Elec}} = CF_{CA} \cdot SF_{ij} \cdot Energy_i \quad (6)$$

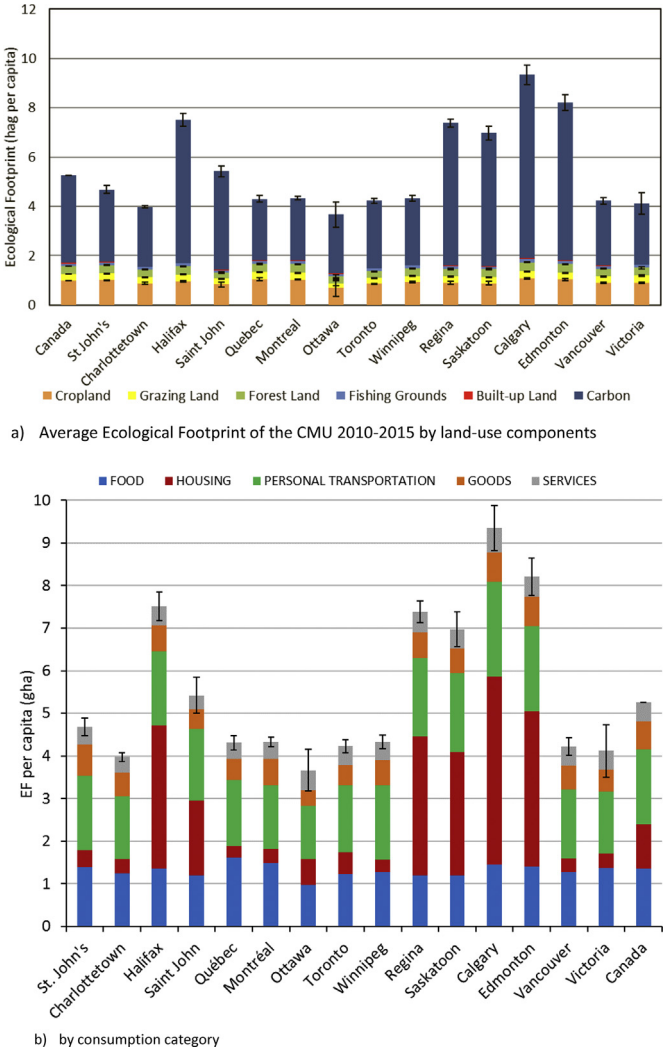

Fig. 5. Average Ecological Footprint of the Canadian CMAs, 2010–2015 a) by land-use components and b) by consumption categories.

3. Results and discussion

3.1. Overview of the Ecological Footprint and carbon Footprint in the 15 Canadian CMAs

The carbon Footprint remains the largest Footprint categories in the 15 CMAs of Canada, on average from 58% in Montreal and Quebec to 80% in Calgary of the total EF across cities, from 2.47 gha per capita in Victoria to 7.46 gha per capita in Calgary (Fig. 5a). Fig. 5 only report the EF from consumption per capita.Fig. 5b shows the EF by household consumption categories. The EF of Vancouver is comparable to the EF from the bottom-up study previously reported (Moore et al., 2013). In this case study, the total carbon Footprint is due 27–59% to personal transportation, 4–56% to housing energy, 6–16% to services, 5–14% to good consumption and 5–15% to food, taking here on average over 2010 to 2015. (Figs. 5 and 6). The error bar in Fig. 5 represents the CF standard deviation between years 2010–2015 for the total carbon Footprint, based on consumption habits.

Within each consumption land-use matrix (CLUM) category, subcategories allow us to further disaggregate the major areas of consumption. . The category personal transportation has the largest Footprint and represents from 27.42% of the total CF in Calgary to 58.97% in Winnipeg (Fig. 7). Personal transportation is further separated in three subcategories: purchase of vehicles, operations of personal transport equipment and transport services, as reviewed in Section 3.3. Purchase of vehicles represents only 4.85% (Toronto) to 10.37% (Regina) of total transportation CF. Operation of personal transport equipment is the main component of total CF associated to transportation: 57.91% (Victoria) to 80.96% (Saint John) of total transportation CF. Transport services also represent a non-negligible portion of transportation CF: 11.26% (Saint John) to 37.17% (Victoria).

For most cities, personal transportation is the largest component of CF. Nevertheless, six cities stand out: Halifax, Saint John, Regina, Saskatoon, Edmonton and Calgary have the largest CF associated with housing, with values ranging from 2.03 (Saint John) to 4.22 gha per capita (Calgary) Our study attempts to explain these differences. Within the CLUM category of housing, a major difference exists in the subcategory 'Electricity, gas and other combustibles.' In fact, for Halifax, Saint John, Regina, Saskatoon, Edmonton and Calgary, this subcategory represents 94.87% (Saint John) to 96.30% (Calgary) of housing CF total, and is analyzed in more detail in the following sections.

3.2. Influence of the electricity source

Canada is the third-largest producer of hydroelectricity in the

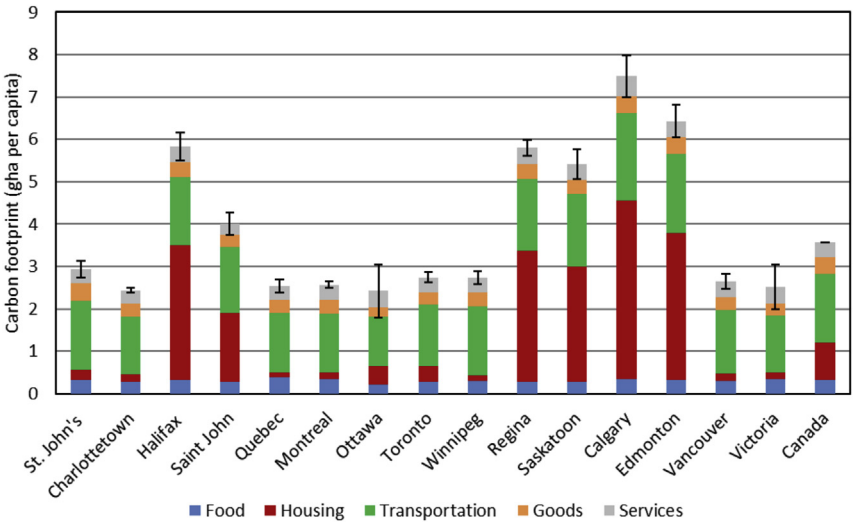

Fig. 6. Carbon Footprint of the 15 CMAs, average for 2010–2015.

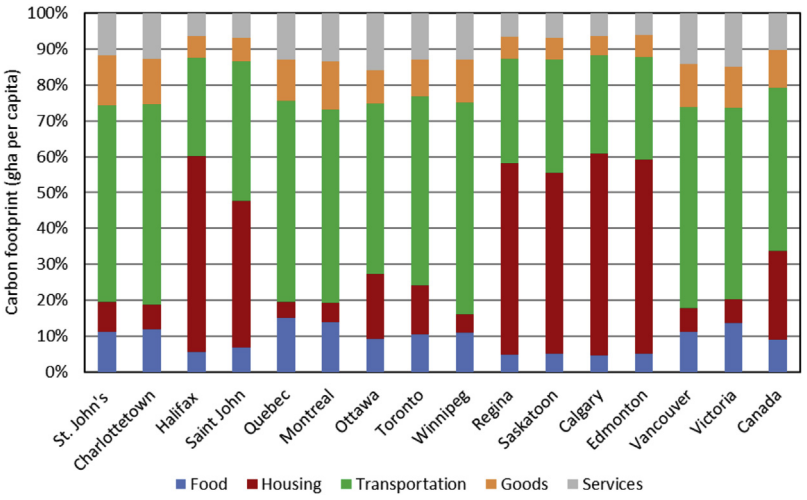

Fig. 7. Relative Carbon Footprint of the 15 Canadian CMAs, average for 2010–2015.

world (Association canadienne de l'hydroélectricité, 2015), after China and Brazil, nevertheless some Canadian provinces continue to power their cities with non-renewable energy. Power sources have a direct influence on the carbon Footprint for each CMA, which allows to highlight low-carbon indicators. Canada CLUM shows that, in the housing category, the subsection 'Electricity, gas and other fuels' represents 80% of the total. Fig. 8 present carbon Footprint for the category 'Electricity, gas and other combustibles' of the 15 Canadian cities average from 2010 to 2015, and the total housing category. Cities with a larger carbon Footprint have more economic activities in the fossil fuel sector.

"Electricity, gas and other combustibles" consumption category creates the biggest gap between cities. They have either a high CF associated to the category or a very low (near zero), although average expenditures are not very different. The energy factor creates the difference to calculate CF of this category. This factor reflects carbon emissions associated to energy use (Supplementary Electronic Table S1). Depending of provinces/territories, in this case, energy factors vary from 0.01 (Quebec) to 5.64 (Alberta). The national average energy factor of Canada is 1 and then other provinces are relative to the Canada average. Cities getting electricity from fossil fuels mostly (coal, natural gas) have high energy

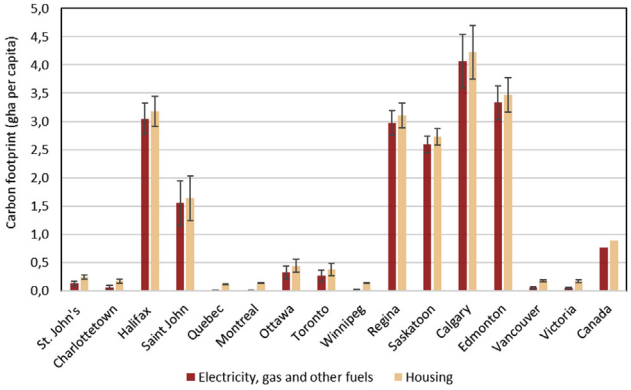

Fig. 8. Carbon Footprint for 'Electricity, gas and other combustibles', average for 2010–2015.

factor. For instance, energy factor of Calgary is 4.88 (the biggest of the 15 Canadian cities), its CF for the category 'Electricity, gas and other combustibles' is 4.08 gha per capita, also the bigger of the 15-Canadian cities.

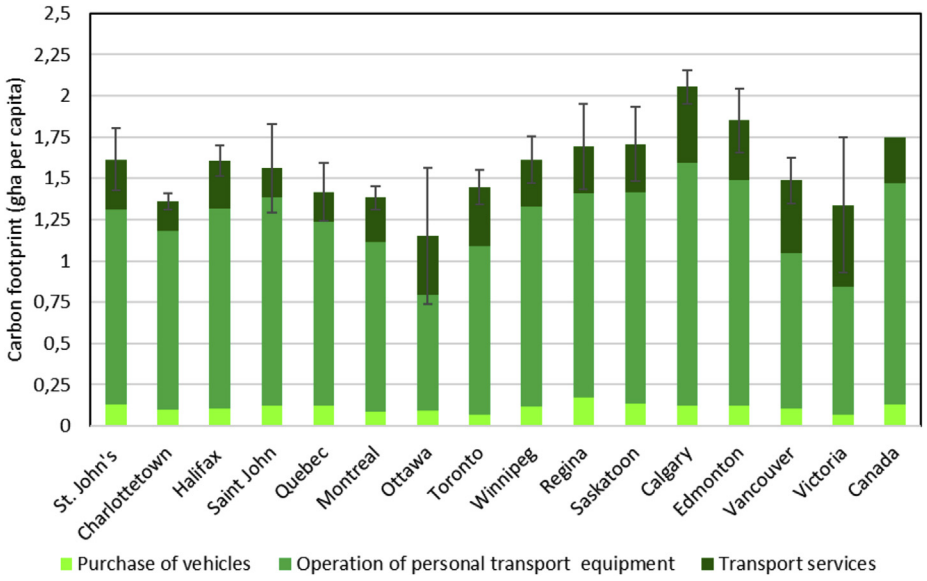

Fig. 9. Carbon Footprint for 'Transportation', average for 2010–2015.

The analysis of power sources in the 15 Canadian cities showed that cities having a carbon Footprint of 2–3 gha per capita (Halifax, Saskatoon, Regina, Calgary, Edmonton, Saint John) use non-renewable energy to produce their electricity (coal, natural gas, oil). Other cities (Québec, Montréal, Winnipeg, Vancouver and Victoria) use only renewable energy, hydroelectricity mostly; thus their carbon Footprint is about 0.01 gha per capita, making it 400% smaller. The electricity source, whether renewable or non-renewable, significantly affects the cities' carbon Footprints.

Renewable energy compared to fossil fuel has a non-negligible effect on CF and EF by extension. In fact, in Canada, the previous analysis shows that using fossil fuel is responsible for the CF gap between cities through the category 'Electricity, gas and other fuels'. Even if power consumption seems to be a significant element of CF variation, power source is certainly one of the most decisive factor. Other researches demonstrate that provinces which produce mostly electricity from hydro power like Manitoba, British Columbia, Quebec and Newfoundland, have a lower CF. In contrary, municipalities in Alberta or Nova Scotia, which depends on coal or natural gas, have a greater CF (Wilson and Anielski, 2005). Thus, to decrease CF, cities as Halifax (Nova Scotia), Saint John (New Brunswick), Calgary, Edmonton (Alberta), Regina and Saskatoon (Saskatchewan) must increase the renewable sources available on their lands and decrease fossil fuel-based electricity production.

3.3. Transportation

Carbon Footprint of personal transportation is strongly dependent of the use of personal vehicle and transport service (Fig. 9). Cities with greater household purchase of fossil fuel (gasoline, diesel oil) have a bigger carbon Footprint for the category operation of personal vehicles. On average, use of personal vehicles represents 60% of the transport category and the subcategory transport service represents about 30%. This trend is reversed in Ottawa and Victoria, which have a larger proportion of Footprint in 'Transport services' compared to 'use of personal vehicles'.

3.3.1. Operation of personal transportation

In 2014, global Canadian transportation was responsible for 23% of global greenhouse gas, which accounts for 172 $MtCO_2$ eq (Environment and Climate Change Canada, 2016b). This amount is due to combustion of fossil fuel (oil, diesel), which create non-negligible GHG emissions. According to data of Statistics Canada, expenditures linked to 'Gas and other fuels' represents 40% of total expenditures linked to 'Private use of vehicles'. Fuel consumption for personal vehicles has a direct effect on CF associated to 'Private transportation'.

Automobile fuels are taxed by federal and provincial governments, they are calculated as a percentage and a cent amount added to the total (Table 1 and Supplementary Table 2). At federal scale, tax is permanent (10 cents per oil litre and 4 cents per diesel litre). At provincial scale, it is variable, thus oil price is depending on municipalities. In addition, three cities (Vancouver, Victoria and Montreal) also add a supplementary tax. According to data of Statistics Canada, people in cities with the high fuel taxes (Quebec, British Columbia), spend less for fuel than other cities, while the taxes do not have the same effect in St. John's. Fuel taxes can encourage citizens to use other means of transport than their private vehicle and other instruments are also needed.

To gain more insight into the CF of the 15 Canadian CMAs

Table 1
Adjusted expenditures for 'Gas and other fuels', average for 2010–2015.

	Gas and other fuels ($CA moy)	% of total Private Transportation expenditures	Taxes (%): GST/HST, Provincial Tax	Taxes (¢): Federal Excise Tax, Carbon Tax/Levy, Provincial Fuel Tax, Transportation Taxes
Saint John	1139.93	45.73	15	25.5
Regina	1078.04	40.03	5	25
St. John's	1067.96	44.31	15	43
Calgary	1052.54	40.85	5	23
Edmonton	1008.12	41.13	5	23
Saskatoon	1003.50	41.71	5	25
Charlottetown	952.99	44.77	15	23.1
Halifax	897.12	40.73	15	25.5
Québec	887.90	39.65	14.975	29.2
Winnipeg	882.02	40.38	5	24
Ottawa	868.19	39.22	13	24.7
Toronto	838.18	42.72	13	24.7
Montréal	788.50	43.17	14.975	32.2
Vancouver	736.44	33.60	5	35.5
Victoria	677.13	36.00	5	28

associated to 'Private transportation', we analyzed per capita fuel use. Data of fuel sales (Gouvernment du Canada, 2016) and data of the province's population (Government of Canada, 2017) allow to calculate oil and diesel consumption per capita between 2010 and 2013. The current national dataset does not differentiate gasoline from diesel, thus the consumption is not adjusted for carbon fuel intensity. Ontario, Quebec and British Columbia consume less fuel (oil and diesel) (Supplementary Tables 3 and 4). According to CF (Fig. 9), cities in these provinces have the lowest CF for the category 'Operation of personal transportation'. In the contrary, citizens in Alberta consume the biggest amount of fuel, CF of the same category for Calgary and Edmonton are also the highest.

For most metropolitan regions, the Footprint of the CLUM category 'Operation of personal transportation' represents approximately 60% of CF total (Fig. 10). Fuel consumption is the reason of this proportion. Nevertheless, variations between cities could be due to others key factors like urban planning, urban morphology, and accessibility of transport services. To define with precision why it remains variable, it is necessary to obtain more specific information on citizens' transportation, such as average car occupancy; kilometres travelled per passenger by private vehicle and by various transport services, average fuel economy.

3.3.2. Transport services

Victoria, Ottawa, Vancouver and Toronto have the largest CF associated to the CLUM category 'Transport services'. They have also a smaller CF for 'Operation of personal transport equipment'. Citizens tend to use more transport services over their personal vehicles. In addition to transportation by personal vehicles, use of transport services such as bus, rail or commercial flights requires the combustion of fossil fuels and results in GHG emissions. According to Statistic Canada data of this study, average adjusted expenditures associated to transport services are extremely variable between cities. Charlottetown (Prince Edward Island), Saint John (New Brunswick) and Quebec (Quebec) citizens had relatively low average expenditures (250–330 CPI adjusted CAD, Table 2) compared to citizens of Calgary, Edmonton (Alberta), Victoria, Vancouver (British Columbia), Ottawa and Toronto (Ontario), whose average expenditures were much higher (620–830 CPI adjusted CAD, Table 2). For Quebec and Saint John, the category 'Transport services' represents just 5–6% of total transport expenditures, respectively; while in Vancouver and Victoria, it represents 17% and 20% of total transport expenditures, respectively.

Regarding CF, estimated from expenditures, 'transport services' represents 11.3% (Saint John) to 37.2% (Victoria) of total transportation CF. The portion of 'transport services' varies depending on cities. In fact, it is possible to classify cities in three ranks

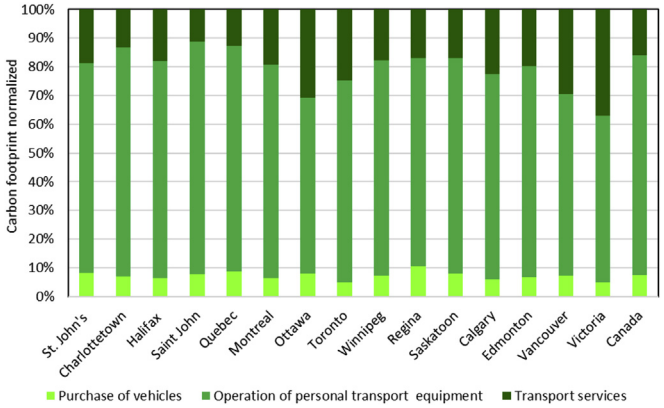

Fig. 10. Normalized Carbon Footprint associated to 'Transport', average of 2010–2015.

Table 2
Adjusted expenditures for 'Transport Services' and 'Private Transportation', average for 2010–2015.

	Transport Services ($CA moy)	% of total Transport expenditures	Private Transportation ($CA moy)	% of total Transport expenditures
St. John's	539	9.53	5115	90.47
Charlottetown	326	7.01	4327	92.99
Halifax	507	10.09	4522	89.91
Saint John	258	4.62	5321	95.38
Québec	309	6.21	4671	93.79
Montréal	457	11.21	3620	88.79
Ottawa	623	11.91	4606	88.09
Toronto	634	16.01	3326	83.99
Winnipeg	513	11.29	4028	88.71
Regina	500	7.82	5894	92.18
Saskatoon	529	9.73	4902	90.27
Calgary	828	13.84	5158	86.16
Edmonton	629	11.03	5076	88.97
Vancouver	745	16.02	3906	83.98
Victoria	808	19.31	3377	80.69

according to its CF: low, medium and high. According to the number of inhabitants per metropolitan regions (Government of Canada, 2017), areas of lower population and smaller surface area have a lesser CF associated to 'Transport services'. In fact, in these cities, fleet of service vehicles are lower. For instance, Quebec CF for 'Transport services' is of 0.18 gha per capita, *Réseau de Transport de la Capitale* is composed of 582 autobuses of 870 km of networks (Réseau de Transport de la Capitale, 2016). In comparison, Calgary CF for 'Transport services' is of 0.46 gha per capita, Calgary Transit has 1176 vehicles in its fleet for 4369 km of roads, it CF associated to 'Transport services' is the highest of the 15 cities. According to 2011 data, the population of Calgary was 1214839 (5^{th} in the population), while it was 765706 for Quebec City (7^{th} in the population). In terms of the surface area, Calgary is 5108 km^2 (7^{th} in surface area), and Quebec City is 3349 km^2 (11^{th} in surface area). After the link between population size and transport services, there is no direct correlation between surface area, population and transport services of the 15 CMAs, while it can be further investigated later.

The preference use of transport services to personal transportation is the first step to decrease total transport CF. Even if not all passenger vehicles are zero-emission vehicles, it substitutes individual cars to decrease global GHG emissions linked to burning of fossil fuel. According to Toronto Transit Commission (Toronto Transit Comission, n.d.), an autobus replace 45 cars, a tramway replace 95 and a subway train replace up to 910 cars. Transport is one of the main EF components on which each person can act directly. On the side, municipal government have to take action to find alternatives to the excessive use of personal vehicles: transport services more accessible and useful, ease active transport (Wilson and Anielski, 2005).

3.4. Carbon Footprint from services

The service category is made of 15 CLUM subcategories; Fig. 11 shows the most important ones. The total service CF varies from 0.27 gha per capita in St John to 0.47 gha per capita in Calgary. The average service CF for the 2010–2015 period is 0.36 gha ± 0.04 for the 15 CMAs. Financial services is the dominant source of carbon impact, from 0.17 gha per capita in Calgary to 0.07 gha per capita in St. John's. The variability in financial services expenditure is higher in Victoria and in Ottawa. Victoria and Vancouver have higher expenses in services per capita, while the service consumption has a lower Footprint, which can explain the lower EF.

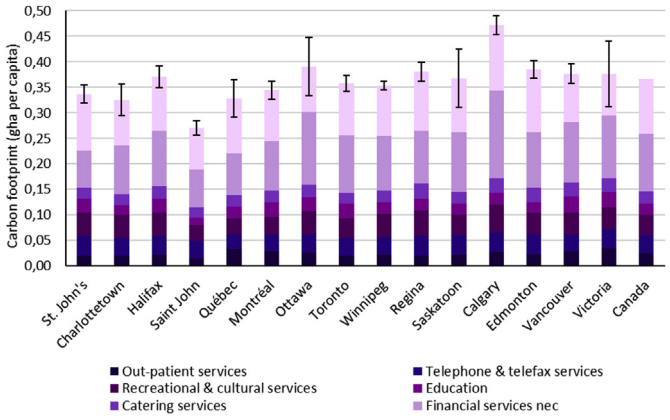

Fig. 11. Carbon Footprint of the most important subcategories of the services consumption category, average for 2010–2015.

3.5. Carbon Footprint from goods

The good consumption is composed of 15 subcategories. Fig. 12 shows the total CF for the total good consumption (CMAs' average for 6 years: 0.34 ± 0.06 gha) and highlights the contribution of most important categories. The standard deviation is presented on the total, as in the other figures. The total CF from the good consumption category varies from 0.23 gha per capita in Ottawa to 0.42 in St John's. Clothing has a dominant impact on CF and represents 26% of the CF in Halifax, while it represents 44% of the CF in Ottawa. Most clothes are imported from abroad. Citizens of Ottawa did not significantly report tobacco consumption in 2010–2015. Tobacco was not recorded every year in a number of cities, which explains the larger variability in the good CF. The tobacco footprint in Halifax is higher, also because it was more often disclosed, which can be checked later by other means. When comparing the two cities located on islands, St. John's and Victoria, Victoria has a carbon Footprint a quarter lower than the most eastern city. Urban areas are known to have multiplication of consumption outside their budget and living environment (Heinonen and Junnila, 2014). Surprisingly, the consumption habits in Toronto and Vancouver, ranked 1 and 3 respectively in population size, have a good consumption lower than the average and than Canada, which means that an optimization is taking place.

3.6. Food consumption

The food category of carbon Footprint represents an average of 0.32 ± 0.04 gha per capita. It includes solid food, non-alcoholic beverages and alcoholic beverages with the former having the most significant impact of the three subcategories as it represents 81–88%. The other subcategories are low carbon Footprint indicator as they suggest 0.03 to 0.06 gha, as shown in Fig. 13. Essentially, solid food subcategory's high carbon Footprint can be explained by the use of energy during the production phase and the post-production significant use of fossil fuel (Bellarby et al., 2008). Although these are not the only sources of GHG as fertilizer, manure and livestock feeding processes are significant as well (Canada, 2009).

The solid food subcategory includes several components such as bakery products; cereal grains and cereal products; fruit, fruit preparations and nuts; vegetables and vegetable preparations; dairy products and eggs; meat; and fish and seafood. As the CLUM is not calculated at this level, the study of the tendency of food consumption is done using the annual surveys of household spending. This data allows to study the ratio of dietary components among the cities, part that will be exposed in detail further. Food subcategory does not include food from restaurants nor catering service as it is part of the Service category. Ottawa and Victoria both have missing data in the SHS with respectively 2 and 1 year missing. This data was not considered in the calculation of the average of the cities, thus only the data from 4 and 5 years respectively were used instead of 6 for those cities.

Regarding both studies, CF and household spending, when two CMAs are considered in a province, the one being the capital tend to have the highest food Footprint and highest food consumption spending, for instance, Quebec, Ottawa and Victoria, while it is not the case for Edmonton. These three cities also represent the highest food CF within the study. CMAs with the highest CF are located in the province of Quebec, Ontario and British Columbia. As shown in Fig. 14, some of these cities also have the highest food consumption expenditure such, as Quebec and Victoria.

The expenditure subcategorie that has the most impact in the differentiation among the cities is 'dairy products and eggs.' According to Vergé et al. (2013) dairy products and eggs are significant sources of carbon dioxide emissions because the process needs many interventions that involve fossil fuel and electricity use, such as the production of fluid milk, cream and butter. Besides, his study reflects the influence of context (i.e. climate, on-farm practices and energy sources) on the EF and the CF of dairy farming among the cities and provinces. Furthermore, the meat subcategory has the largest portion of the expenditure for the food and is constant between cities. Many studies have already stated the influence of the meat on the EF and CF (Galli et al., 2017; Song et al., 2015). Beef has the largest CF, with 32 kg eqCO_2 per kg of meat, followed by pork and poultry with respectively 10 and 6.9 kg eqCO_2 per kg of meat, mainly due to the use of farm machinery and the carbon

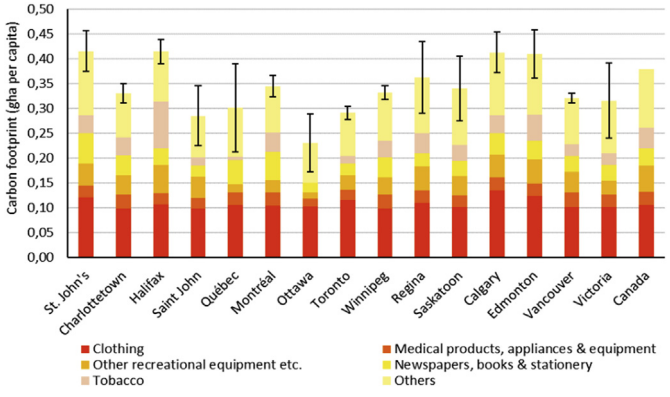

Fig. 12. Carbon Footprint of the most important subcategories of the goods consumption category, average for 2010–2015.

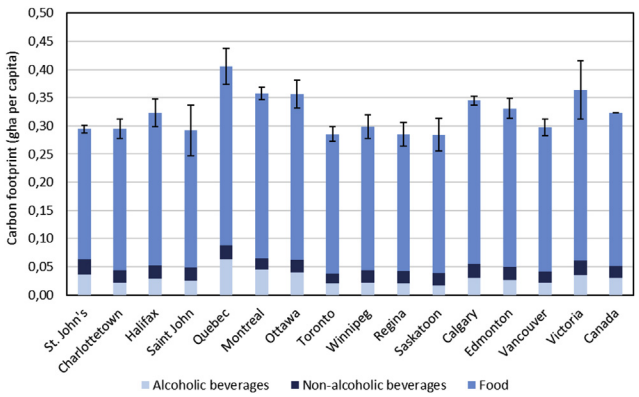

Fig. 13. Carbon Footprint for 'Food', average for 2010–2015.

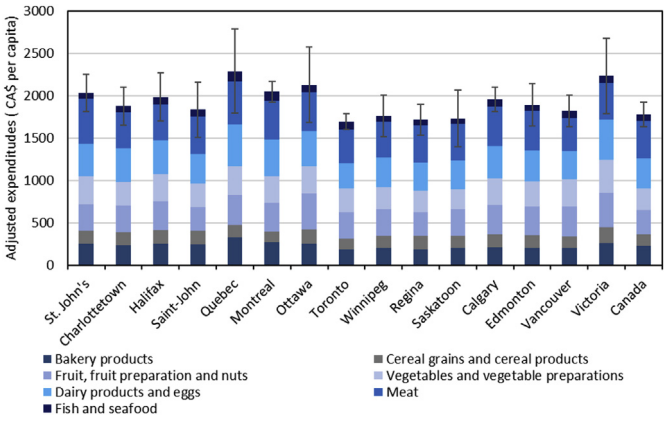

Fig. 14. Distribution of food consumption expenditure average for 2010–2015.

stocks contained in the soil that is released during the production of cereals for their feeding (de Vries and de Boer, 2010). In this study, the meat consumption was stable between cities, while it is an opportunity to reduce the food footprint (Treu et al., 2017; Veeramani et al., 2017). Ultimately, the food category might not have CF as pronounced as the housing category, but has a significant impact on other land uses as cropland and fishing ground. Indeed, it is important to note that the food category represents an average of 27% of the Canadian EF.

3.7. Trends toward low carbon

First, power source carbon intensity is the most significant factor creating a non-negligible gap between cities. In fact, municipalities using non-renewable sources tend to have CF around 3 gha per capita for the category "Electricity, gas and other fuels". On the contrary, the other which operates renewable power as hydro, have a lesser CF, around 0.05 gha per capita for the same category. Transportation services also contribute to reducing the carbon footprint of transportation and imply shifting transportation habits (Ottelin et al., 2017). Spending per capita is higher in the service category, while it has the lowest impact of the Carbon Footprint. There are also opportunities to reduce to the carbon Footprint of the food and good consumption.

Metropolitan regions can become the leaders for post-carbon urban mobility transition. City governments can play a major role as powerful catalysts for investments in urban mobility. Municipal governments need to invest in new ways of transportation (electric transport services) to give an example to smaller cities and all together create a real revolution in transportation. Nowadays, 90% of global mobility use oil products to work and urban mobility follows the way of thinking, "drive anywhere at any time". Moreover, vehicles often have one passenger and in the future, it might be zero with autonomous cars. Citizens have to adapt their mobility, because of ecological issues due to burning of fossil fuel. Means of transportation, such as the use of transport services, is another low carbon indicator. Electric vehicles are an opportunity to decrease carbon emissions linked to transit, which are part of the decarbonization parthway for Canada (Vaillancourt et al, 2017). In fact, electricity may be the product by renewable sources. Another alternative is fossil fuel is biofuels. First generation uses corn, which is, cultivated on cropland firstly reserve for human food. So this generation cause an issue because of conflicts on land use. Mobility and food do not have to interfere. However, researchers work on a new generation of biofuels to remove this conflict of interest. Biofuels will be an efficient solution if it is produced from forest waste or organic waste for instance. Nevertheless, it is necessary to replace actual vehicles by technology that is more efficient, to optimize transportation services and mobility patterns. .

The urban planning of the CMAs can be changed to reduce the carbon Footprint. The optimization of urban form can play a major role in the long term per-capita resource efficiency of a city. Our study shows that the three biggest CMAs of Canada (Toronto, Montreal, Vancouver) have a lower CF than the Canadian average, especially in housing and transportation, which means that an optimization with taking place with a larger population and higher population density. However, a parallel consumption may take place with urban citizens (Heinonen et al., 2013), which was not analyzed here. The sharing economy can help to reduce the carbon footprint of transportation, good and services consumption. Optimization of the urban form can increase the use of renewable energy in cities (Sarralde et al., 2015), which is especially needed in cities relying on non-renewable energy sources. Urban sustainability is rooted in urban morphology (Bourdic et al., 2012) and more studies are needed. The long-term goal for urban citizens is to rely more on local resources.

4. Conclusion

Using a top-down (MRIO based) approach to derive consistent Ecological Footprint results comparable across multiple cities, we analyzed 15 Canadian CMAs as a case studies to test the applicability of the Ecological Footprint, specifically the carbon Footprint component and its subcategories, as a metric to monitor and identify targets for climate change mitigation. For the purpose of CO_2 reduction, we show how the carbon Footprint of consumption can be disaggregated into household final-demand sub categories and compared across multiple cities, as an outcome metric to understand overarching trends and specific factors leading to the differences we observed. Across all cities, we find that the energy source (renewable vs nonrenewable) is the most influential factor in determining the CF of cities. Further, transportation was the largest component of the CF, regardless of energy source composition. This study indicates that recent efforts towards climate mitigation, such as increasing support for renewable energy instead of fossil sources and the shift from private vehicles towards transport services, and highlights the variability of these factors in Canadian cities. These effects should be supplemented with studies on the long term effects of urban form. Further study to link specific actions, factors, behaviours, values, and processes within each municipality to the Footprint outcomes identified here are needed to assist policymakers in decision-making towards resource efficiency and sustainability policy. This study also identified areas to continue the research, such as methodology based on the SHS and parallel consumption of urban citizen, which can have an impact on cities EF and CF analysis.

The actions needed to achieve the goal of global sustainability, as measured through the Ecological Footprint, overlap with and are indeed highlighted by the Paris Climate agreement at the 2015 United Nations Climate Change Conference, COP 21, which emphasized the need for climate change mitigation through the reduction of CO_2 emissions. By identifying high Footprint intensity consumption we are able to understand the major factors affecting city-level Ecological Footprints. While this study analyzes final household consumption, it is evident that systemic change in urban form, energy production, and economic policy regarding fuel use are key factors in climate change mitigation, that can enable deeper changes in mobility habits, lifestyle and values. In fact, the most influential factors identified here require major infrastructure and/or policy change at the municipal level. Nevertheless, current

citizens and newcomers to Canada must be conscious to make sustainable choices and support progressive systemic change that prioritizes the most influential needs for climate change mitigation. Research, which provides outcome measures, is key for this prioritization and allows people to understand their real impacts of their environment. In fact, a deeper analysis of household consumption and its carbon environmental impact is further needed in sustainability research.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2017.10.189.

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